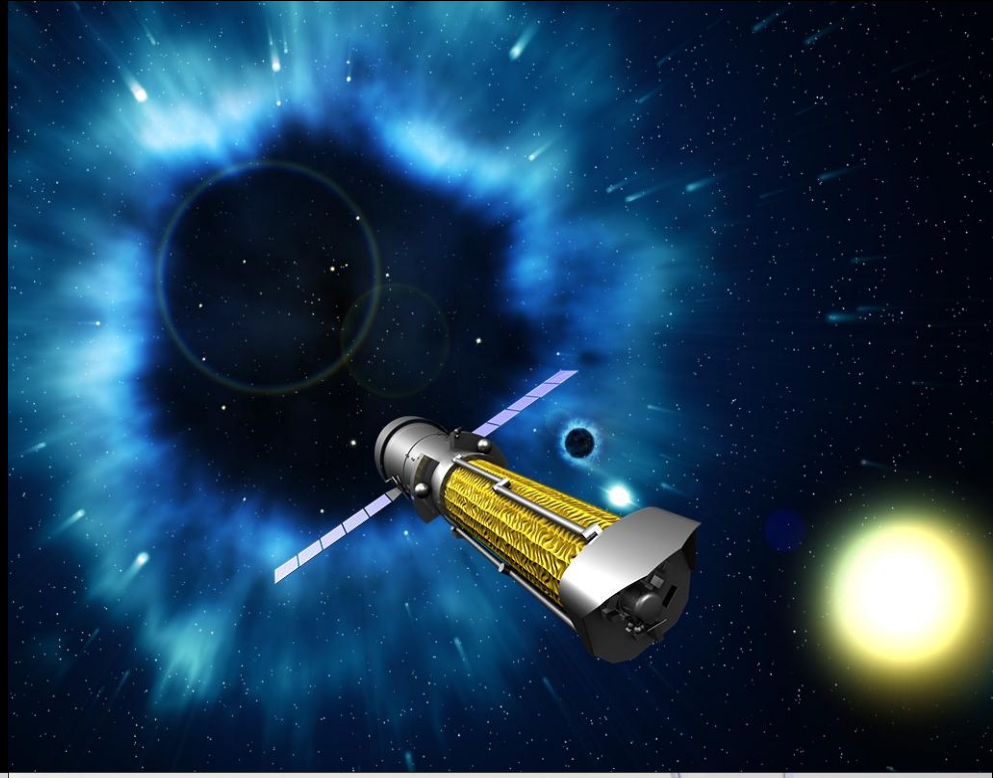
Semiconductor detectors for IXO and more

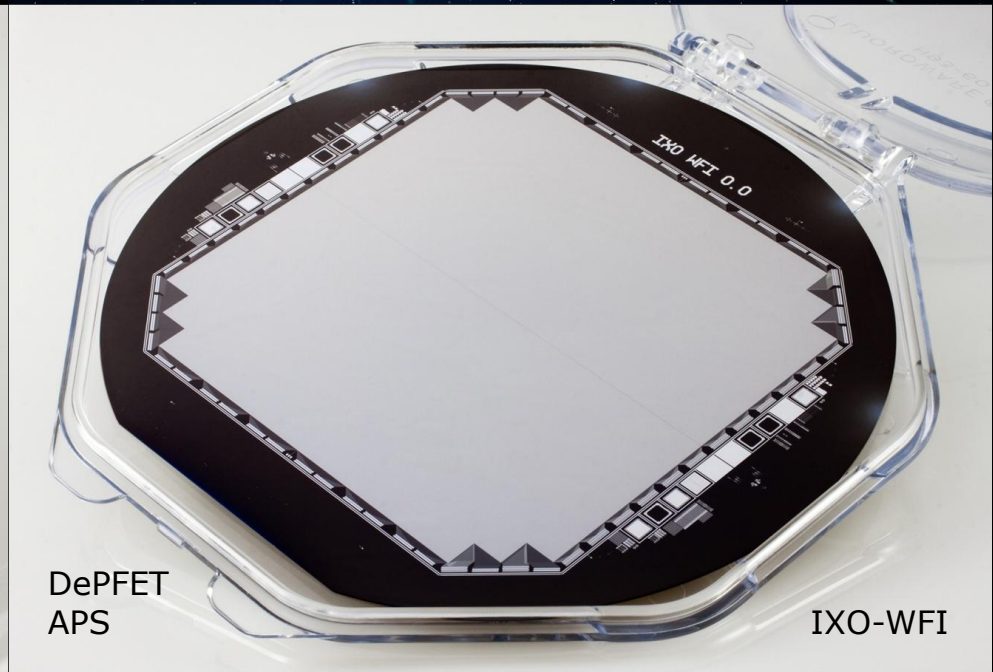
Peter Lechner
PNSensor & MPI HLL

Experimental High Energy Astrophysics
Challenges for the new Decade

Tübingen, 16.07.10



SDD IXO-HTRS



DePFET
APS IXO-WFI

- diode
  - ▷ electronic noise

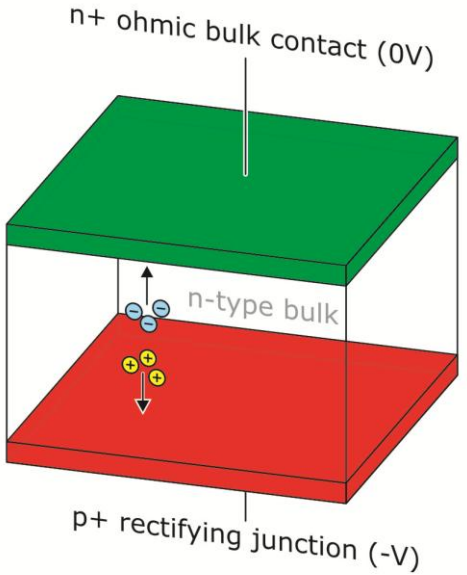
$$ENC = \sqrt{\alpha \frac{2kT}{g_m} C_{tot}^2 A_1 \frac{1}{\tau} + 2\pi a_f C_{tot}^2 A_2 + q I_L A_3 \tau}$$

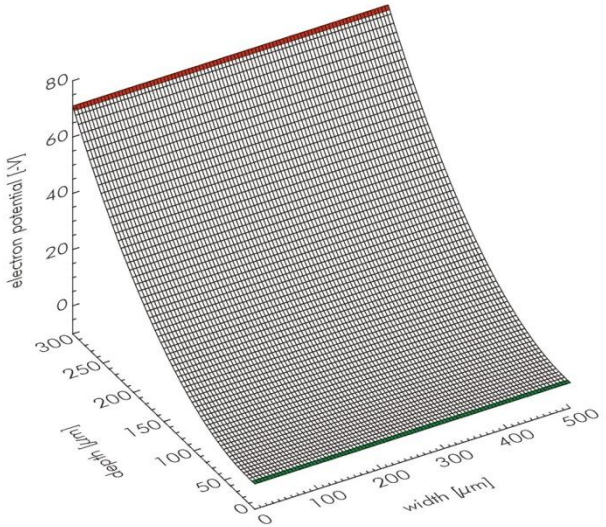
  - ▷ optimum shaping time

$$\tau_{opt} = \sqrt{\frac{2A_3}{A_1} \frac{kT}{q} \frac{C_{tot}^2}{I_L} \frac{2}{3g_m}}$$

  - ↳ for
    - **good resolution**
    - **high count rate capability**

    the capacitance must be minimised!!

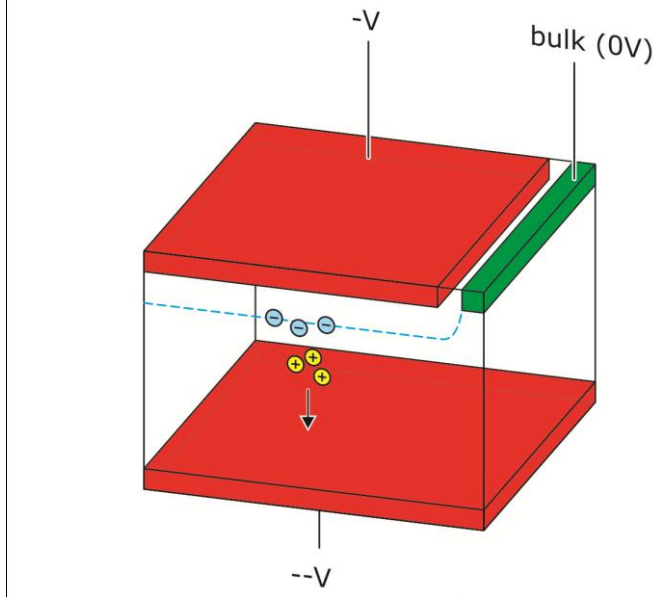


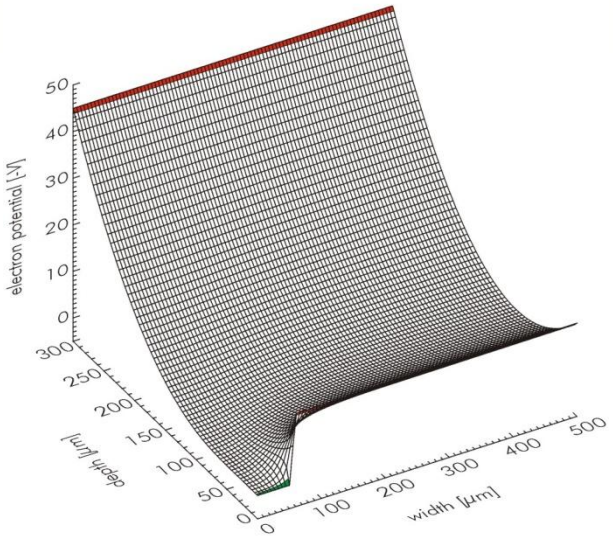


- sideward depletion structure

  Emilio Gatti & Pavel Rehak, 1983

  - ▷ symmetric bias
  - ▷ volume is fully depleted by reverse biased diodes on both surfaces
  - ▷ minimum capacitance of bulk contact, independent of overall area
  - ▷ potential minimum for majority carriers (electrons @ n-Si) in the center plane





  - ▷ asymmetric bias
  - ▷ vertical shift of the potential minimum

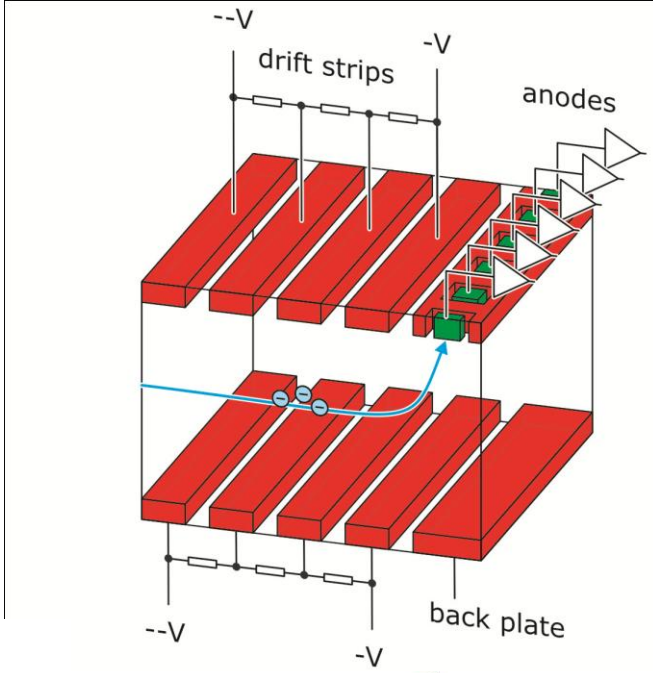
  ?? signal extraction ??

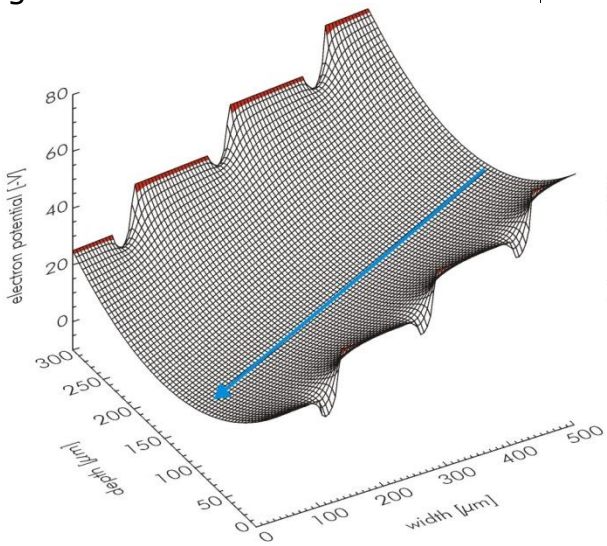
  ↳ **advanced detector concepts**

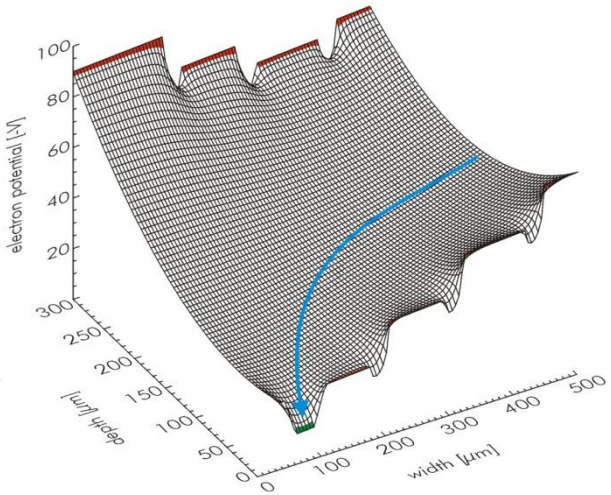
- linear silicon drift detector (SDD)

  Emilio Gatti & Pavel Rehak, 1984

  - ▷ segmentation and bias of diodes
    - ↳ drift field || surface
  - ▷ 2dim position resolution by
    - drift time measurement (trigger!)
    - segmentation of the anode
  - ▷ application: particle tracking



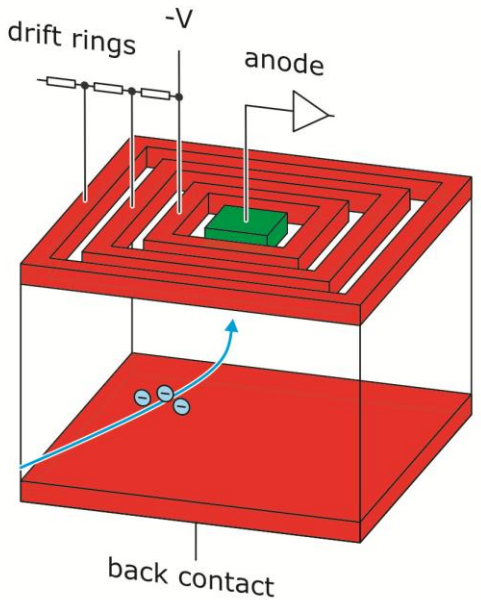


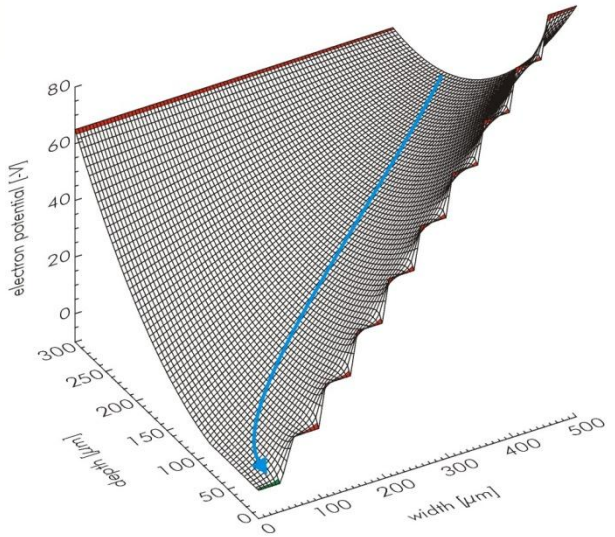


- spectroscopy SDD

  Josef Kemmer & Gerhard Lutz, 1987

  - ▷ one-sided field strip system
  - ▷ non-structured backside diode
    - ↳ optimized for photon spectroscopy
    - ↳ irradiation through homogeneous thin entrance window
  - ▷ integrated 1st FET
    - ↳ low noise
    - ↳ robust against pickup & microphonic noise

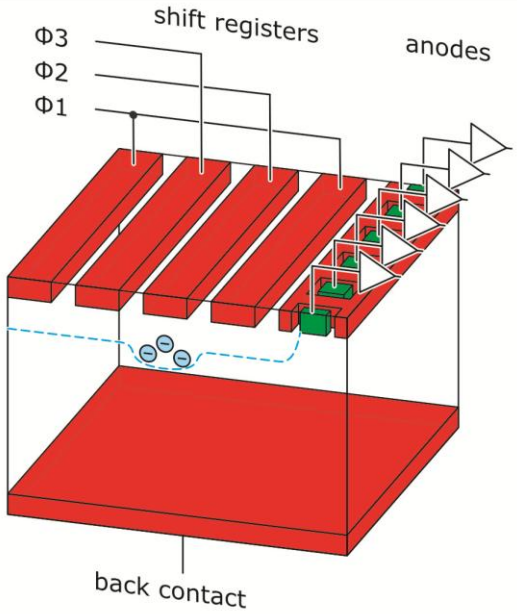


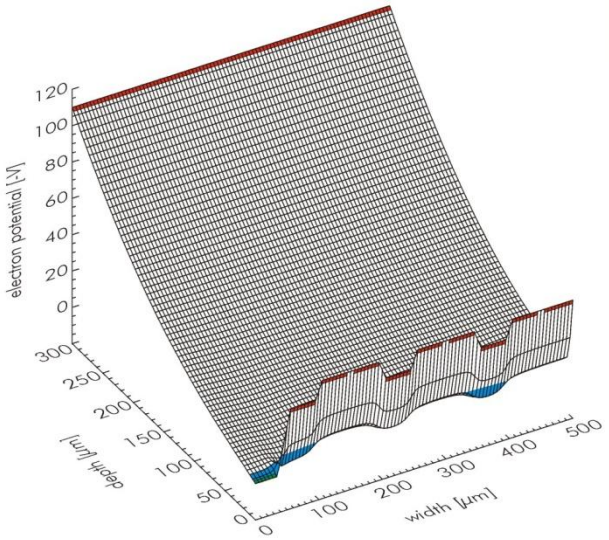


- pnCCD

  Lothar Strüder et al., 1987

  - ▷ definition of potential pockets by differently reverse-biased diodes
  - ▷ charge transport by periodic clocking of shift registers
  - ▷ column-parallel readout
    - ↳ high frame rate
  - ▷ integrated 1st FET (1 / column)
    - ↳ low noise
  - ▷ backside illuminated, fully depleted
    - ↳ quantum efficiency

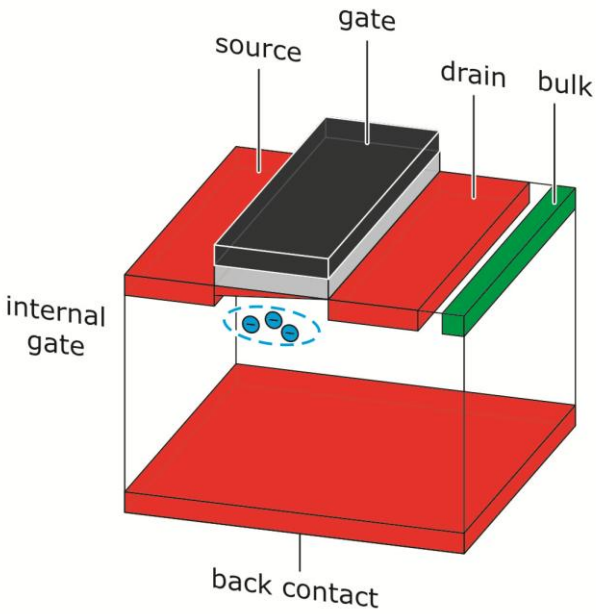


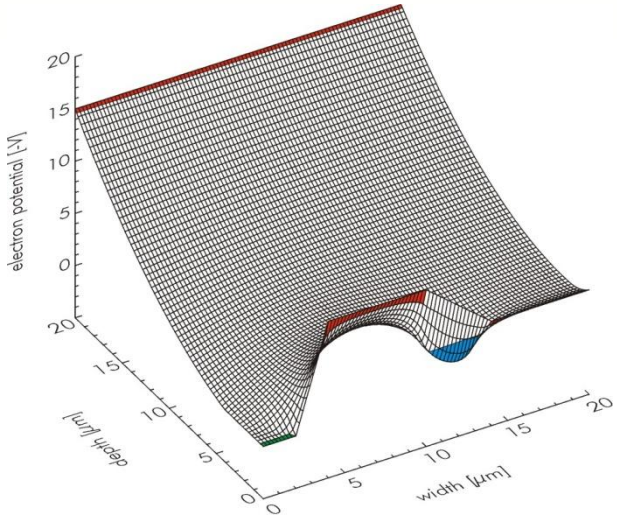


DePFET

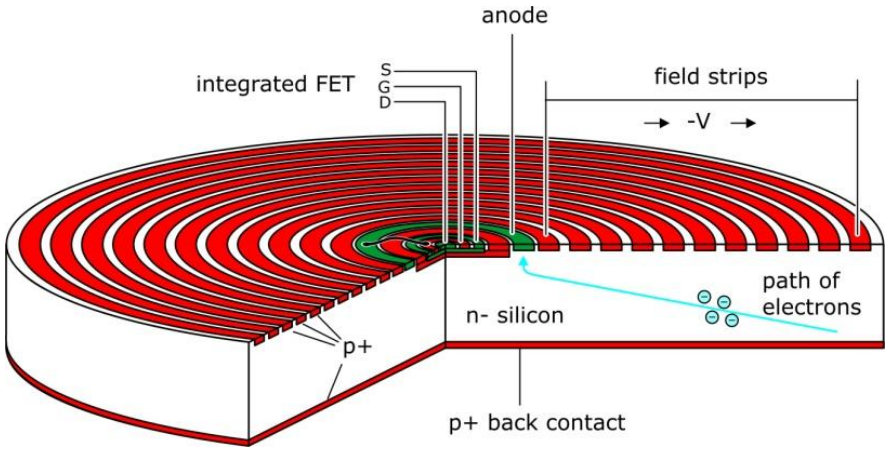
Josef Kemmer & Gerhard Lutz, 1987

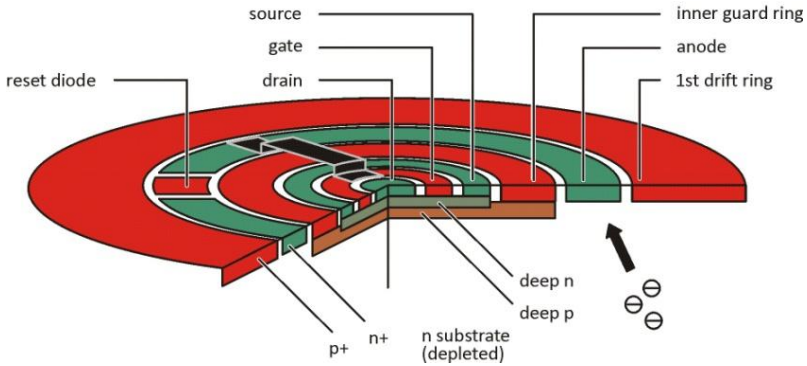
- p-MOSFET on depleted n-substrate
- combined detector & amplifier function
- localized potential minimum under gate = 'internal gate'
  - ↳ modulation of FET current (300 pA/el.)
- low capacitance (20 fF) and noise
  - ↳ excellent spectroscopic performance
- charge storage capability
  - ↳ readout on demand
- non-destructive readout
  - ↳ potential of repetitive readout
- complete clearing of signal charge
  - ↳ no reset noise
- backside illuminated, fully depleted
  - ↳ quantum efficiency

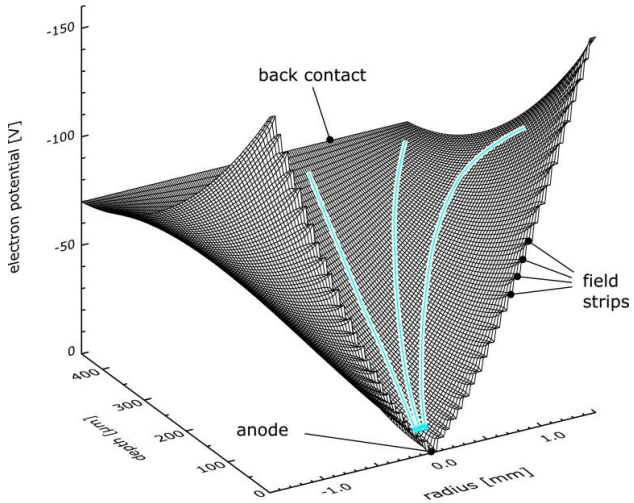




- large sensitive area
- small capacitance + integrated FET
  - low electronics noise
  - high count rate
  - insensitive to pickup & microphony
- low leakage current level
  - room temperature / moderate cooling
- homogeneous entrance window
  - backside illumination
- flexible in shape and size
  - 5 … 100 mm²
- multichannel arrays



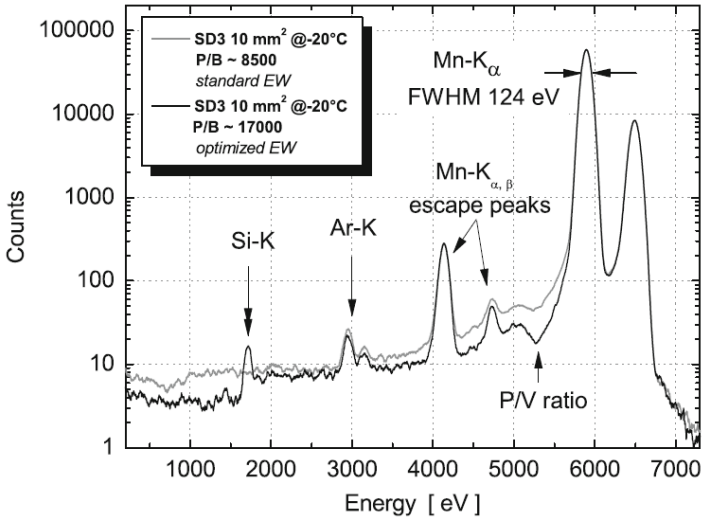




- spectroscopy
  - ▷ SDD 10 mm², -20 °C
  - ▷ energy resolution

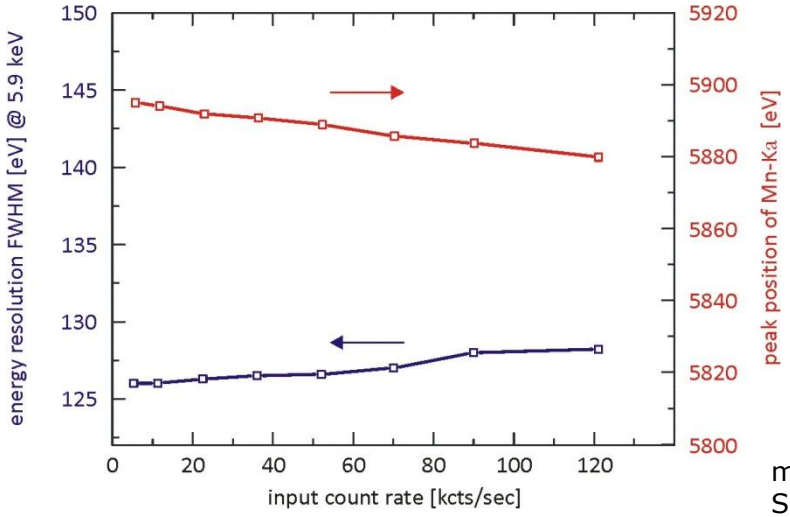
    124 eV FWHM @ 5.9 keV
  - ▷ peak / background ratio

    8.500 … 17.000 @ 6 keV / 1 keV



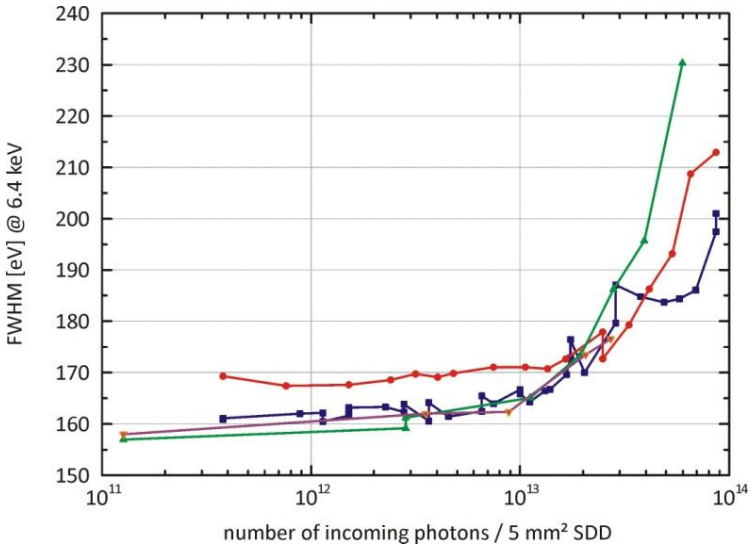
measured
SDD 10 mm²

- count rate capability
  - ▷ charge sensitive amplifier configuration
  - ▷ pulsed reset
  - ▷ stable performance up to > 100 kcps
    - resolution ~ % level
    - peak position ~ ‰ level



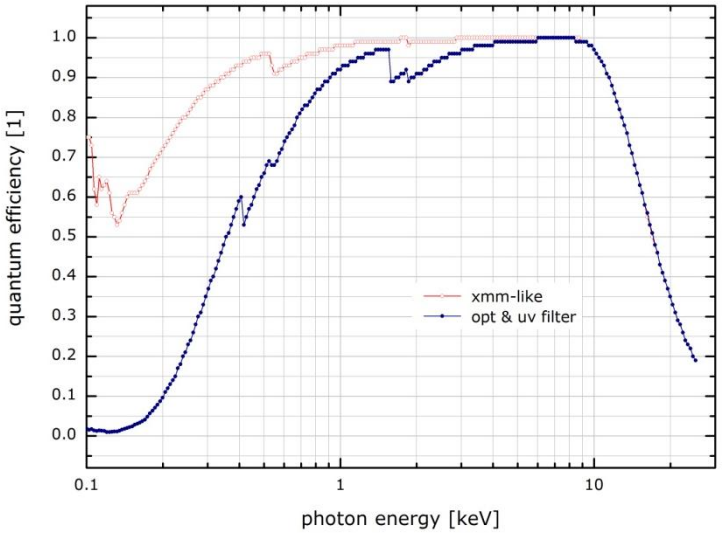
measured
SDD 5 mm²

- long term stability
  - ▷ no effect up to 10^{13} photons
    (18 keV, 300 µm thick device)



measured
SDD 5 mm²

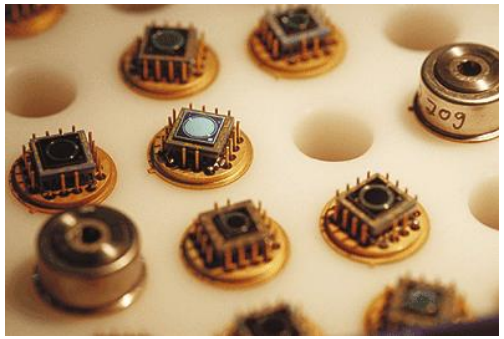
- quantum efficiency
  - ▷ low energy limit
    radiation entrance window
    (Si dead layer, light blocking filters)
  - ▷ high energy limit
    Si thickness, 450 µm

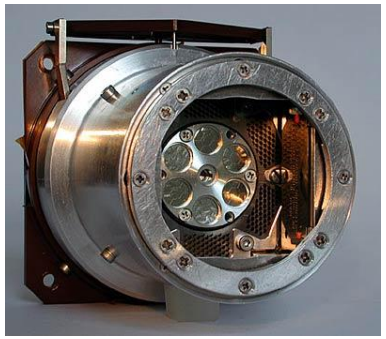


measurement
& model data

- NASA Mars Exploration Rovers
  Spirit & Opportunity
  - ▷ arrived in jan04
  - ▷ scheduled for 3 months / 600 m
    but still active (> 6 years / > 7 km)
  - ▷ APXS (α-particle X-ray spectrometer)
    by MPCh/Mainz on robotic arm
  - ▷ SDD 10 mm² & 244Cu sources
  - ▷ PIXE, composition of rocks
  - ▷ also on ROSETTA comet lander (2014)
  - ▷ X-ray spectra of Marsian samples

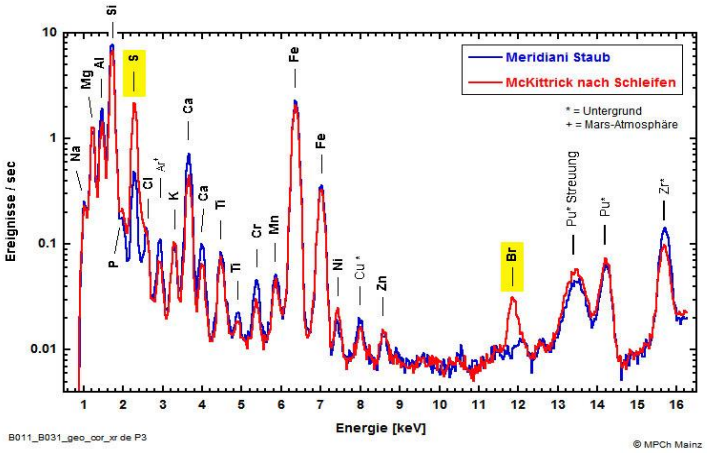
NASA Mars
Exploration Rover

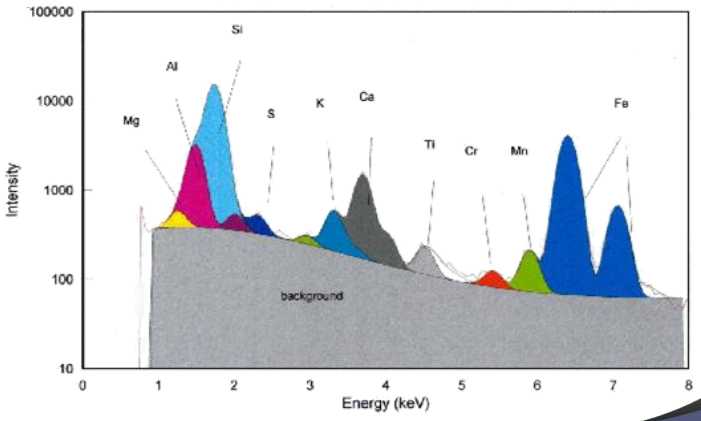




APXS instrument with
10 mm² SDD module

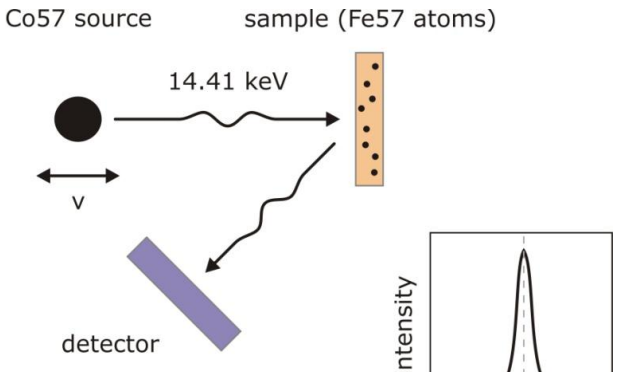
SDD
Opportunity
MER
(2005)



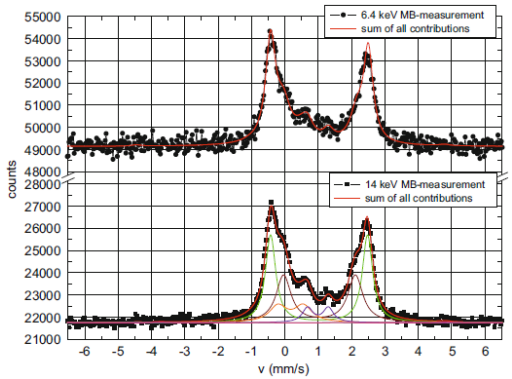


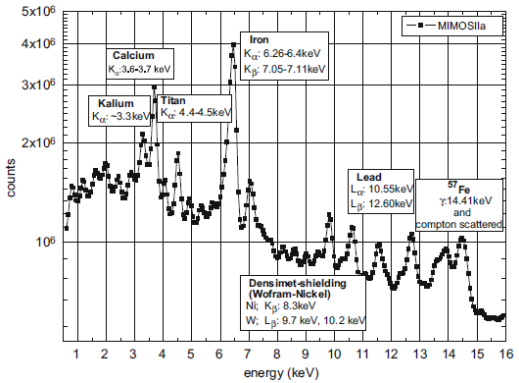
PIN-diode
Sojourner
Pathfinder
(1997)

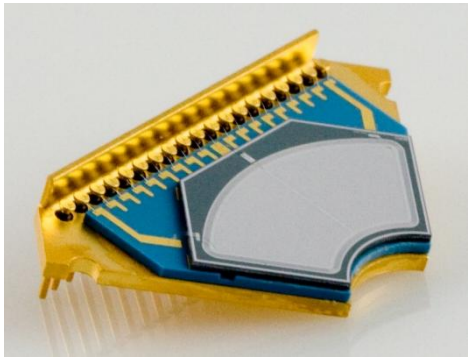
- Mößbauer spectroscopy
  - ▷ resonant recoil-free emission/absorption of γ-rays by nuclei of solid-bound atoms
  - ▷ nuclear levels of emitter/sample shifted and hyperfine split by chemical environment
  - ▷ probing of levels by red/blue-shift
  - ▷ resolution $E/\Delta E \sim 10^{12}$
  - ▷ MIMOS-IIa (Uni Mainz)
  - ▷ 8 x 45 mm² SDDs
  - ▷ simultaneous XRF
  - ▷ ExoMars mission
  - ▷ demonstration at Hawaiian volcano crater



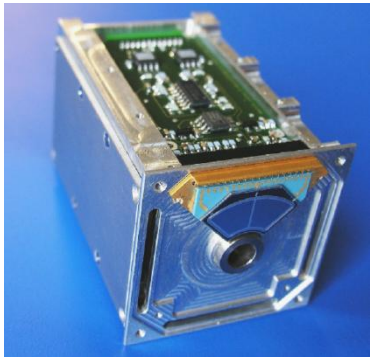
Mößbauer setup (backscattering)



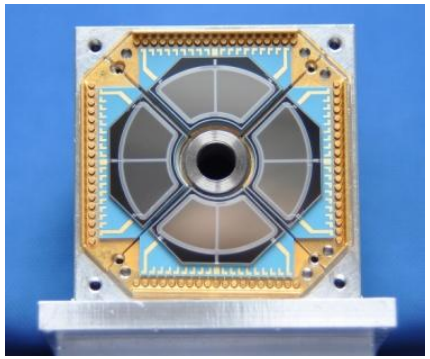




SDD module, 2 x 45 mm²



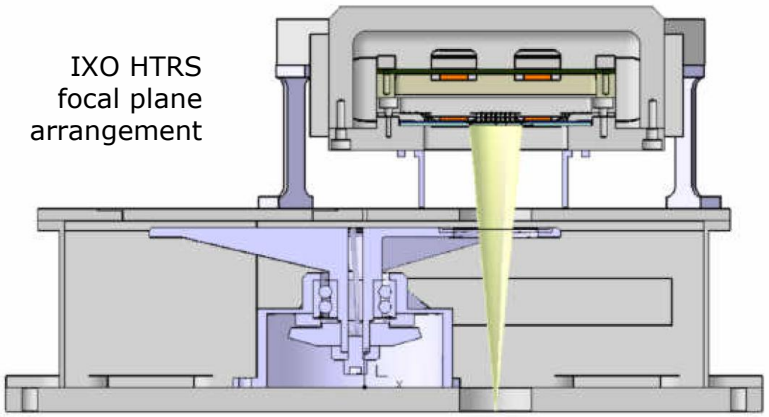
MIMOS-IIa assembly



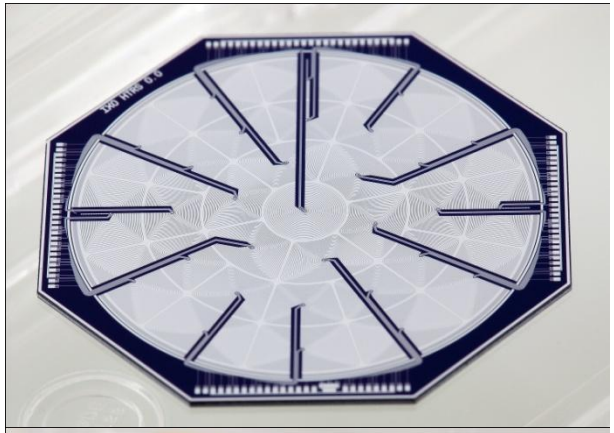
MIMOS-IIa sensor head

G. Klingelhöfer
Uni Mainz

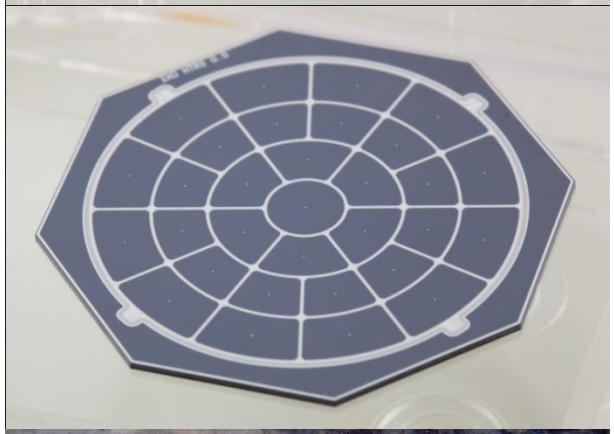
- IXO High Time Resolution Spectrometer
  - ▷ X-ray timing & spectroscopy
    - time resolution 10 µsec
    - 150 eV FWHM @ 6 keV
    - < 2 % pileup & deadtime @ 1 Crab
  - ▷ multi-channel SDD, 31 x 14.6 mm²
  - ▷ out-of-focus distance 11.3 cm
  - ▷ r/o electronics development
    - 8-channel analog ASIC (τ ~ 600 nsec)
    - digital chain (τ ~ 200 nsec)
  - ▷ 7-cell prototype SDD available end10



IXO HTRS focal plane arrangement



mechanical sample: readout side



radiation entrance window side

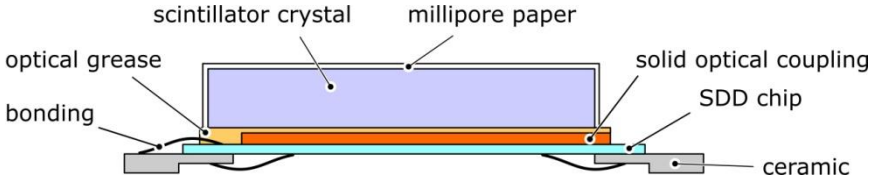
'spider web' collimator for split event supression

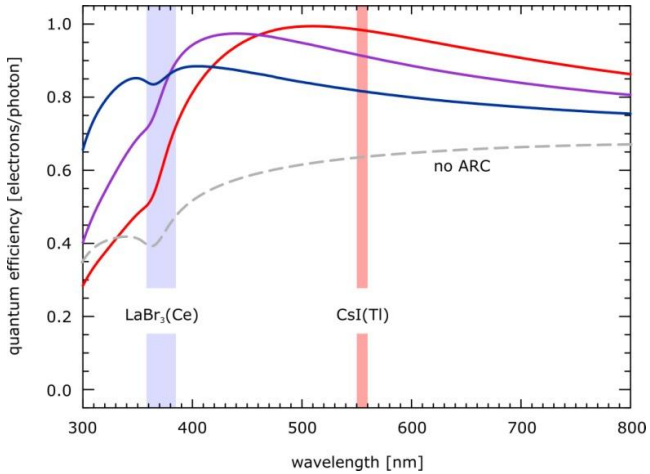
200 µm spokes
10 % coverage

- γ-ray spectroscopy
  - ▷ SDD = scintillator readout device, "counting" of optical photons
  - ▷ scintillators

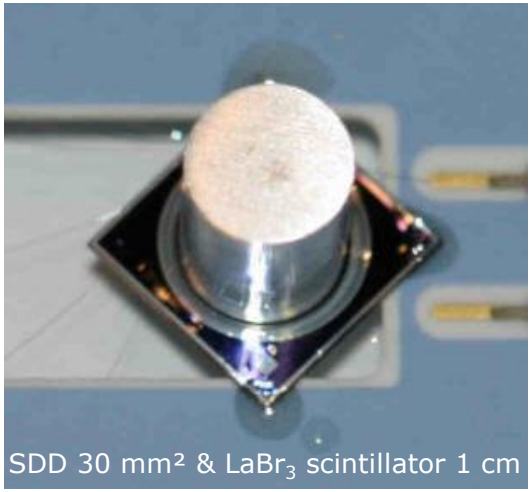
	CsI(Tl)	$LaBr_3(Ce)$
- peak λ [nm]	550 – 565	360 - 380
- light output [ph/keV]	50	60
- decay time [nsec]	1.000	25

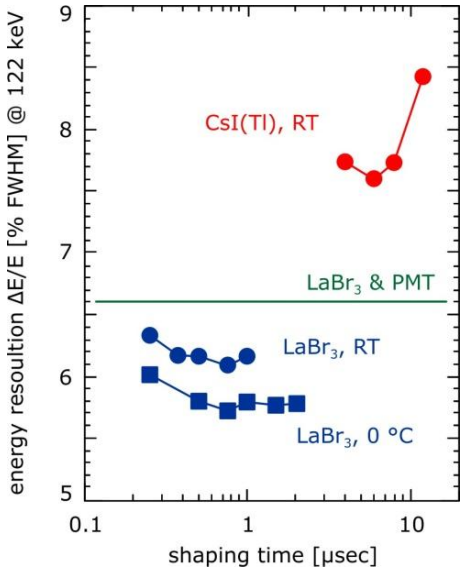
  - ▷ anti-reflective coating (ARC): tuning of entrance window transmittance to scintillator wavelength
  - ▷ example results: SDD 30 mm² (C. Fiorini, Politecnico di Milano)

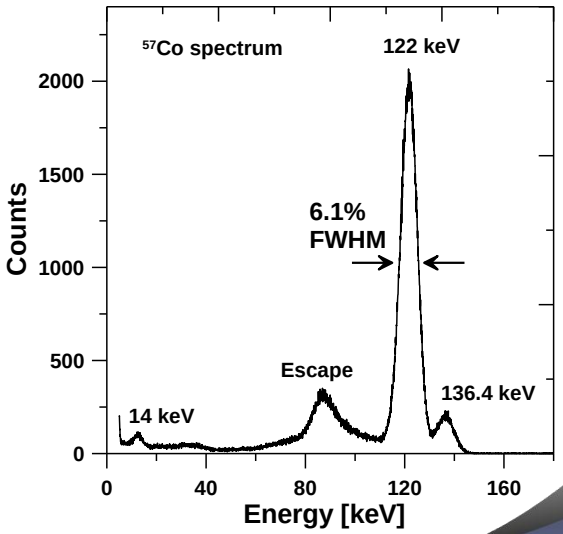




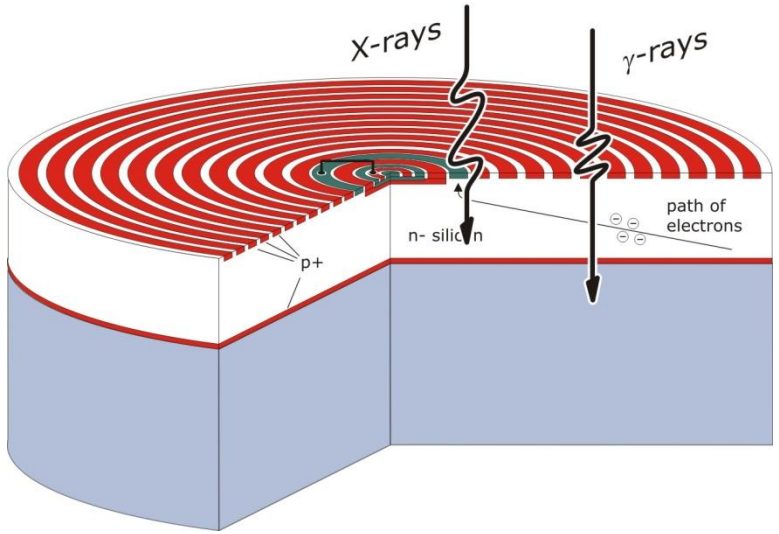
anti-reflective coating

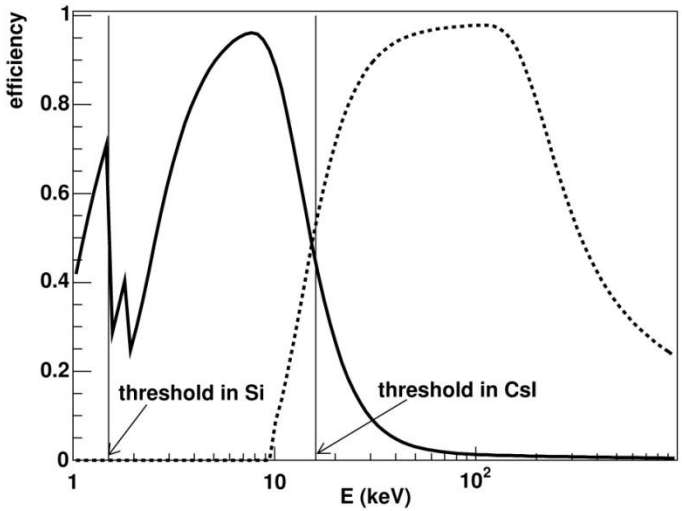


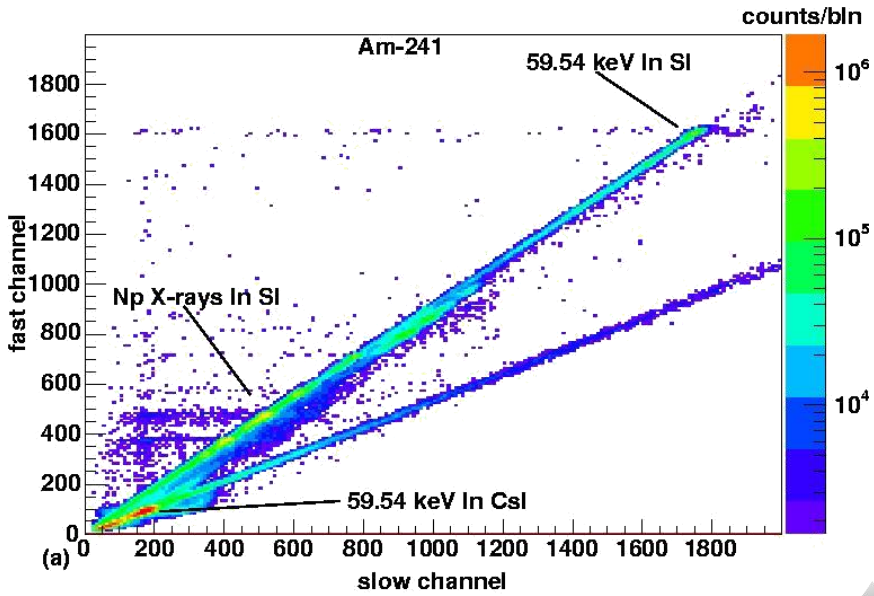




- combined X-ray & γ-ray spectroscopy
  (C. Labanti, M. Marisaldi, CNR-IASF, Bologna)
  - ▷ SDD 10 mm²
    - direct conversion of X-rays
    - low energy threshold: 1.5 keV
  - ▷ CsI(Tl) scintillator
    - sensitive up to 1 MeV
  - ▷ event classification by pulse shape discrimination







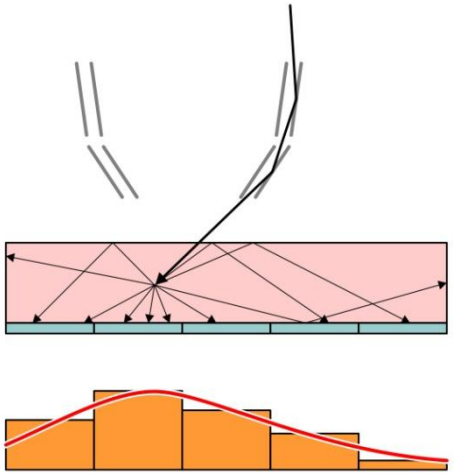
- γ-camera
  - ▷ monolithic scintillator & pixelated SDD
  - ▷ position resolution by centroid of the light distribution
  - ▷ (reduced) energy resolution
  - ▷ e.g. DRAGO (C. Fiorini, Politecnico di Milano):
    - monolithic SDD array, 77 cells
    - cell size: 8.7 mm² = Ø = 3.2 mm
    - area: 2.6 x 2.9 cm² = 6.7 cm²
    - CsI scintillator, 5 mm
  - ▷ spatial resolution

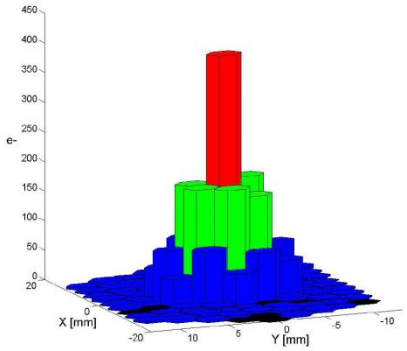
    0.27 … 0.55 mm FWHM

    depending on the position relative to the cell center

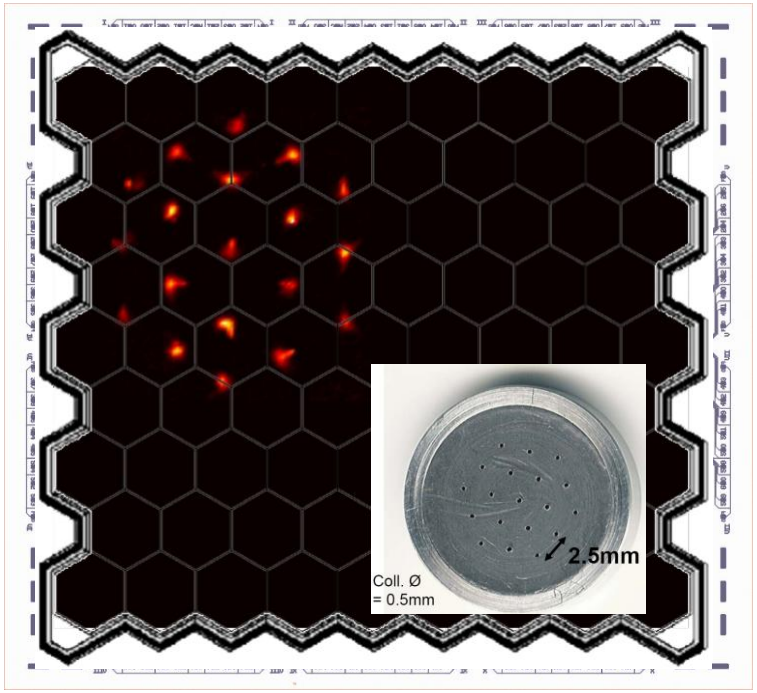
    NB: cell size 3.2 mm, 77 readout channels
  - ▷ comparison

    CdTe pixel detector
    - 300 / 500 µm pixels
    - 7.000 / 4.000 readout channels

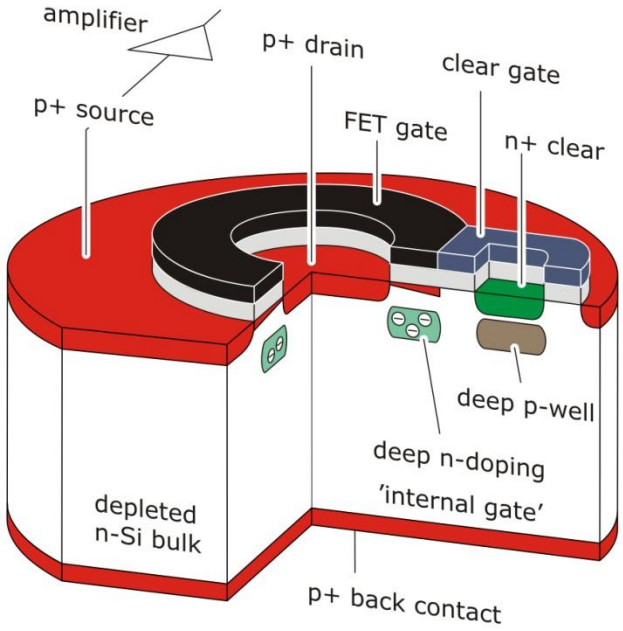


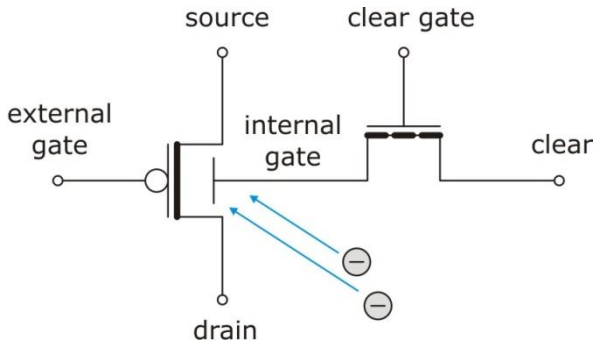


light emission centroid

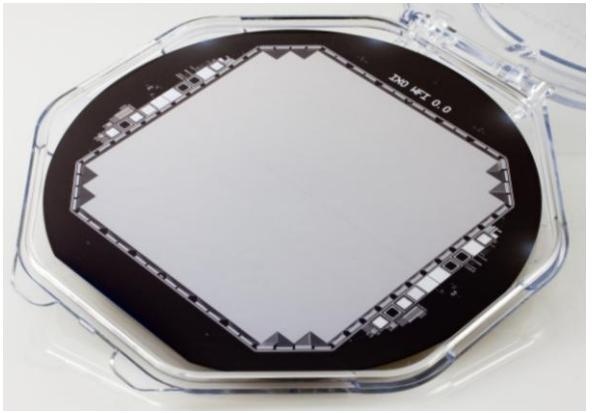


- p-FET on depleted n-bulk
  - ▷ signal charge collected in potential minimum below FET channel
  - ▷ transistor current modulation 300 pA/el.
- combined function of sensor & amplifier
  - ▷ low capacitance (20 fF) and noise
    - ↳ excellent spectroscopic performance
  - ▷ complete clearing of signal charge
    - ↳ no reset noise
  - ▷ non-destructive readout
    - ↳ potential of repetitive readout
  - ▷ charge storage capability
    - ↳ readout on demand
  - ▷ backside illuminated, fully depleted
    - ↳ quantum efficiency

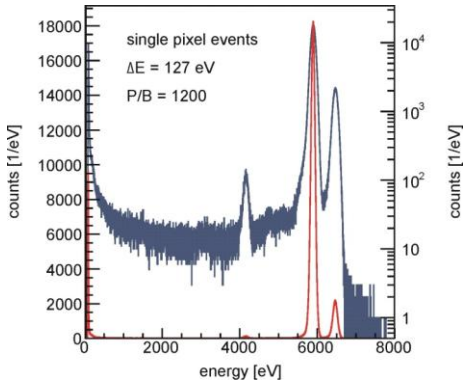


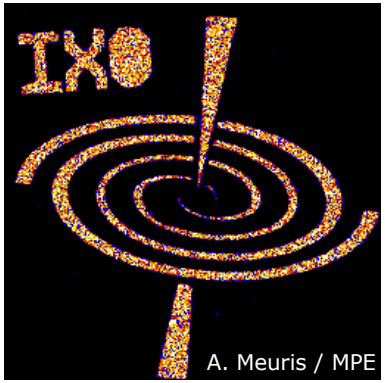


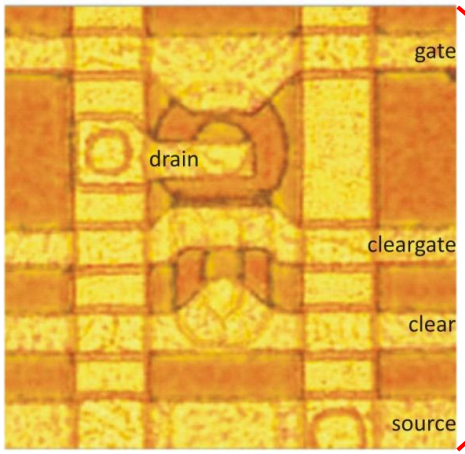
- IXO Wide Field Imager
  - ▷ format
    - 6-inch wafer-scale device, ~ 10 x 10 cm²
    - ~ 1024 x 1024 pixels (100 µm)
  - ▷ framerate ~ 0.5 ... 1 kHz
  - ▷ prototype (XEUS heritage)
    - 256 x 256 pixels (75 µm)
    - 1.92 x 1.92 cm²
    - readout 4 x ASTEROID (6 µsec / row)
    - temperature -5 °C (!)
    - resolution 127 eV (singles)
      140 eV (all)
    - σ (gain, noise, offset) ~ %

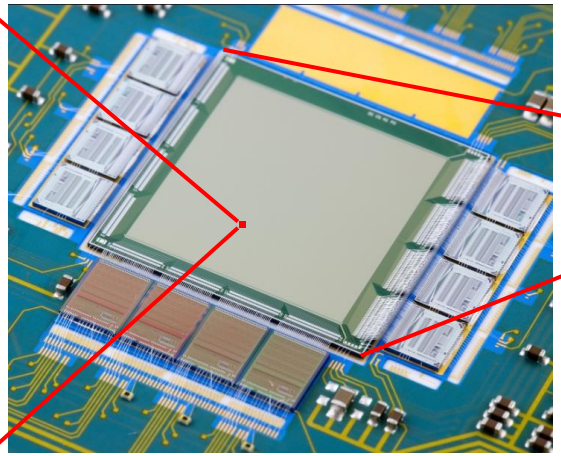


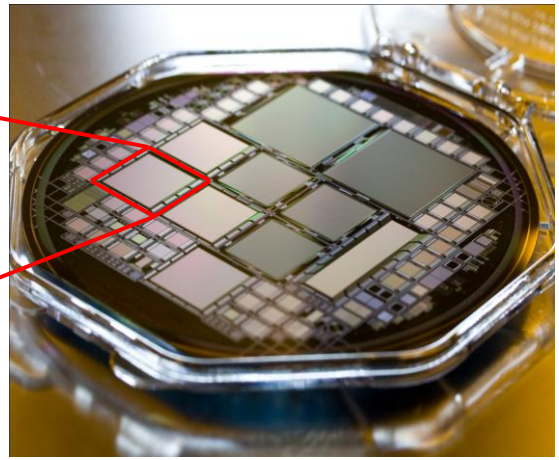
IXO-WFI mechanical sample





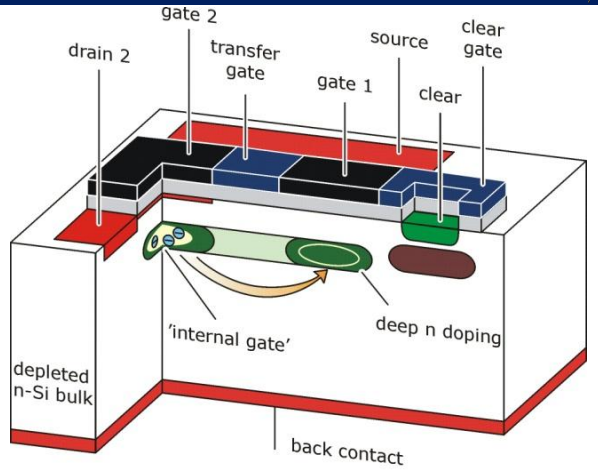


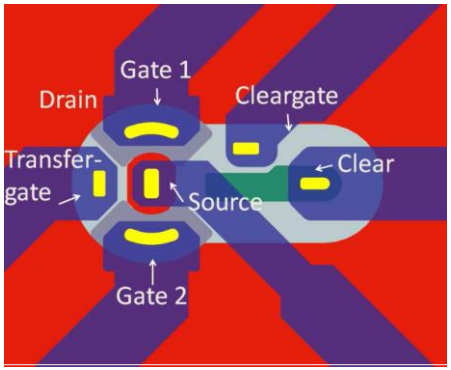




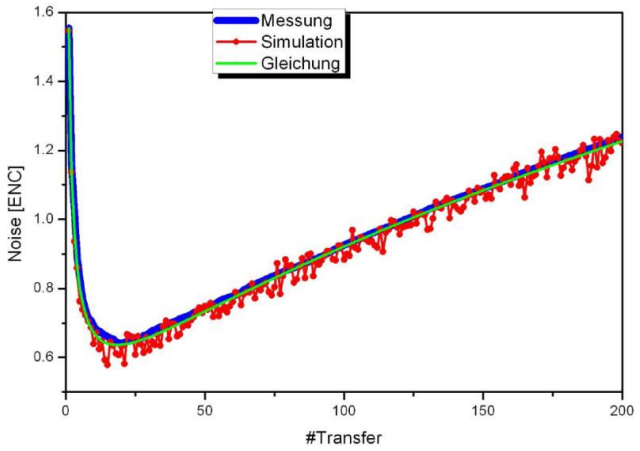
DePFET APS
256 x 256
75 µm pixel

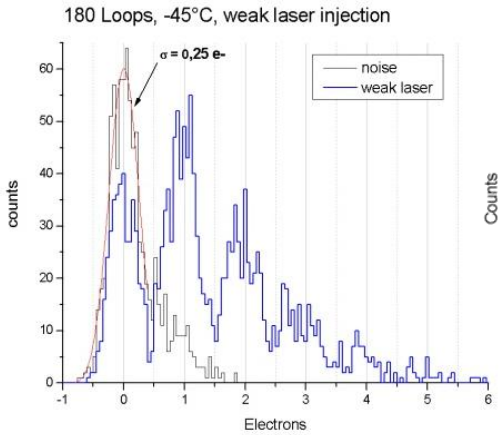
- Repetitive Non-Destructive Readout ("PingPong")
  - ▷ 2 DePFETs per pixel
    - 1 empty / 1 full
  - ▷ intra-pixel charge transfer via transfer gate
  - ▷ elimination of 1/f-noise by independent measurements
  - ▷ noise ~ 1/sqrt(N), N = number of readings
  - ▷ record resolution **σ = 0.25 el.**
  - ▷ 64 x 64 device in production
  - ▷ applications
    - optical metrology
    - optical astronomy

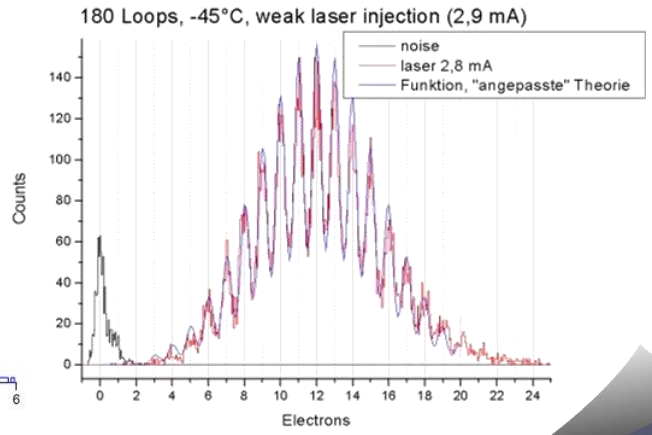




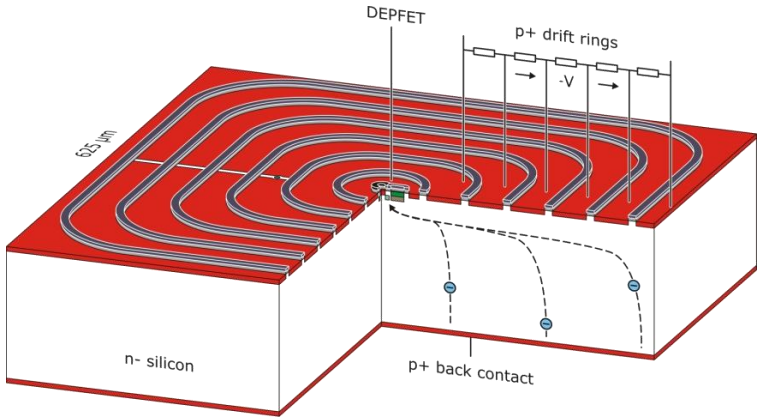
PingPong DePFET compact design

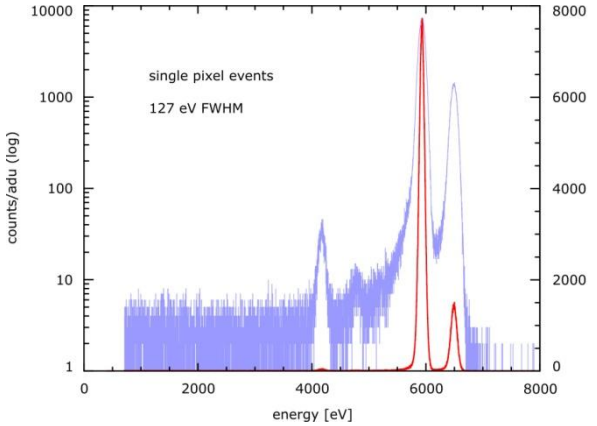


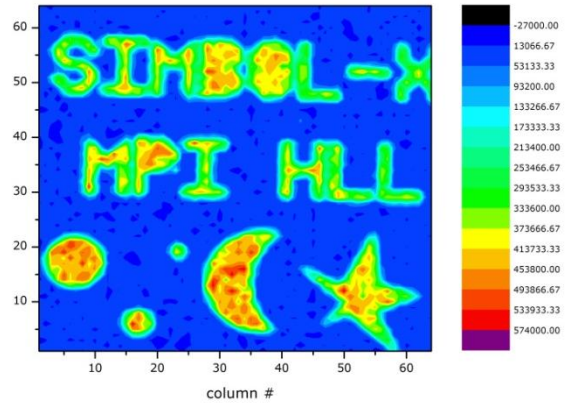


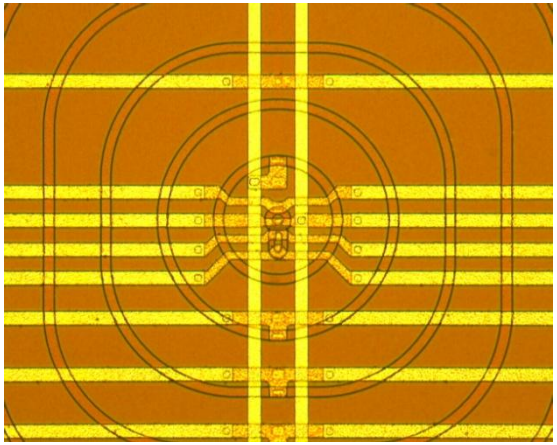


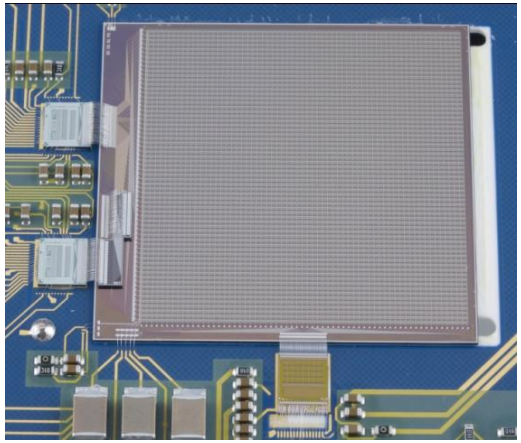
- Simbol-X Low Energy Detector
  - ▷ SDD + DePFET
    macropixel sensor with scalable pixel size
  - ▷ format
    - 128 x 128 pixels (625 µm)
  - ▷ framerate 8 kHz
  - ▷ quadrant prototype
    - 64 x 64 pixels (500 µm)

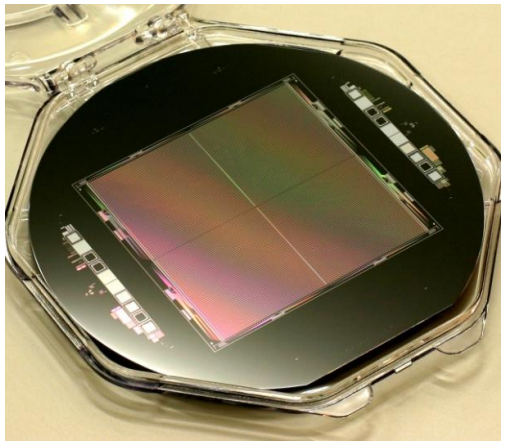




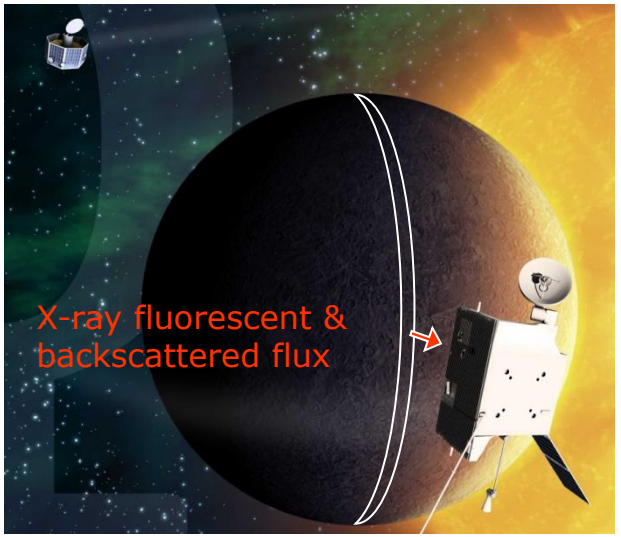


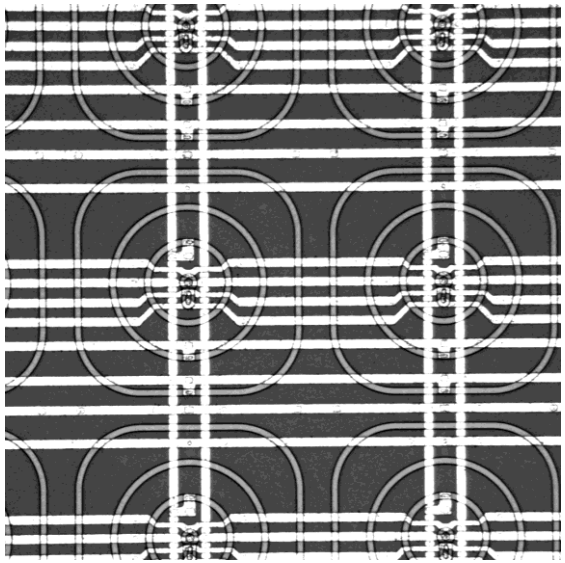


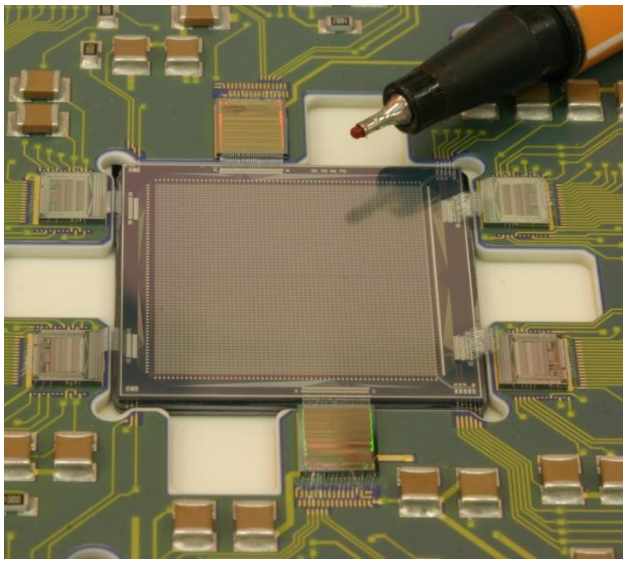


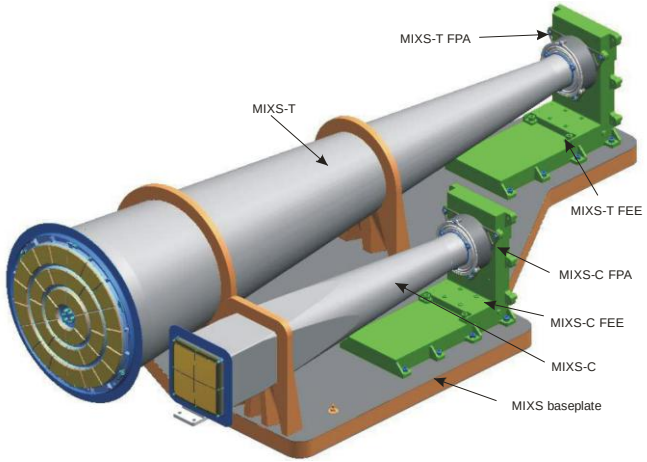


- BepiColombo MIXS
  - ▷ 2 imagers equipped with identical sensors:
    - MIXS-C collimator, wide field imaging (70 – 400 km)
    - MIXS-T mcp telescope, precise mapping (1 – 4 km)
  - ▷ launch 2014, 5 y travel, 1 (+1) y lifetime
  - ▷ challenges: radiation hardness, thermal & power budget
  - ▷ macropixel sensor
    - 64 x 64 pixels (300 µm)
    - 1.92 x 1.92 cm²
    - sensitivity: Fe-L (700 eV) … Fe-K (6.4/7.1 keV)









- many advanced sensor types derived from one intelligent basic structure
- flexible device principles allowing for application specific designs